

Non $q\bar{q}$ light meson spectroscopy.

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Abstract

In this talk I comment on some theoretical expectations for exotic light meson spectroscopy below 2 GeV and their potential interest for a future energy upgrade of DAFNE.

MATTERS OF PRINCIPLE

The colours we perceive around us vary almost continuously between different tones. Only careful scrutiny of the light emitted by pure substances through diffraction gratings at the end of the 19th century demonstrated the separation of these colours into discrete lines, opening a window to a new world of phenomena. In the same way we hope that the spectral lines that form the light of the strong interactions will be resolved and the energy differences between them will help us understand the dynamics of the strong force in detail. With this statement of purpose in mind, in this note I comment on the spectroscopy of light mesons, with special attention to non conventional $q\bar{q}$ states.

The mass gap.

The first observation I would like to make is that the theory of the strong interactions, Quantum Chromodynamics (QCD) *must* present a mass gap. To understand it, think of the meson Fock space of this quantum field theory,

$$|\bar{q}q\rangle, |\bar{q}q\bar{q}q\rangle, |\bar{q}qg\rangle, |\bar{q}qg\rangle, \dots$$

given a state with any particular quantum numbers and a given mass, we could construct another state with the same quantum numbers and extremely close mass by just adding a pair of the current partons to it. Therefore there would be no discrete part to the spectrum at all. This may in fact not be such a bad approximation at high masses, but the low lying states follow definitely a discrete pattern. Therefore, adding a quark-antiquark pair or a couple of gluons to any one state must have an energetic cost, the mass gap. The constituent quark model tells us what the cost of a constituent light quark (u or d) is: 300 MeV, about a third of the mass of the proton. For the strange quark 500 MeV (half of the mass of the ϕ meson) is just about right. There is no consensus on the gluon mass gap, I will give below some indications on this respect.

How many mesons do we know of?

Let me conduct for you the following simple exercise. Take the meson counts (in the sense of “letter counts”, ignore any spin or isospin degeneracies) from the last

PDG listings [1], accept the “established” and “confirmed” resonances as good candidates and bin them, say every 200 MeV. To have a simple theoretical benchmark, construct an arithmetic $\bar{q}q$ quark model in which the quarks cost as discussed in the previous paragraph 300 or 500 MeV depending on flavour, each angular excitation 401 MeV and each radial excitation 700 MeV. The result is plotted in figure 1.

Meson counts from PDG vs “arithmetic” quark model

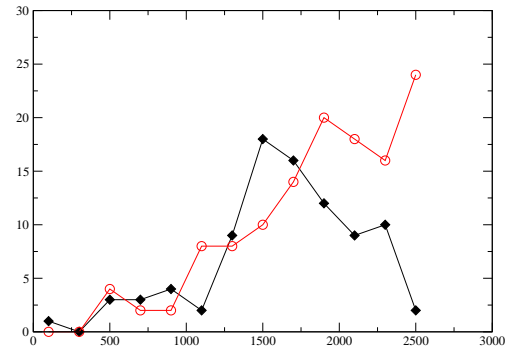


Figure 1: The “arithmetic” quark model meson counts (circles) fall short of detected resonances (diamonds) in the mass region below 1600 MeV.

From the figure one can derive two observations: that the observed number of mesons is more than expected below about 1600 MeV, leading us to conclude that non conventional mesons have already been detected, and second that the meson counts drop dramatically thereafter, even below the minimal quark model expectations. Therefore, there is ample room for the discovery of new resonances, both conventional and nonconventional, in the 2 GeV range.

Exotic mesons

In the conventional quark model, mesons are made of a pair quark-antiquark whose quantum numbers are very simply constructed. In the center of mass frame there is only one orbital angular momentum associated to the relative coordinate \vec{q} and two spins s_q and $s_{\bar{q}}$. Coupling the two spins to give total spin S and then the orbital angular momentum L to give a total angular momentum J leads to the wavefunction $\langle s_q m_1 s_{\bar{q}} m_2 | S m_s \rangle \langle S m_s L m_L | J m_J \rangle Y_L^{m_L}(\vec{q}) \chi_q \chi_{\bar{q}}$. Parity reverses the sign of \vec{q} and the spherical harmonic yields a phase $(-1)^L$, and since the intrinsic parities of particle and antiparticle are opposite, the total parity is $P = (-1)^{L+1}$. To form eigenstates of charge conjugation the two particles need to have the same flavour, in which case applying C reverses their respective role and therefore we collect a phase

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from the spin Clebsch-Gordan and a phase from the spherical harmonic $C = (-1)^{L+S}$. Giving now integer values to L and S , with J taking the values $|L - S|$ to $L + S$ we can construct the ordinary meson quantum numbers J^{PC} :

$$0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}, \dots$$

From the list will be missing the quantum numbers

$$0^{--}, \text{even}^{+-}, \text{odd}^{-+}$$

and a meson in these channels is called J^{PC} -exotic, whereas a meson with ordinary quantum numbers but potentially higher Fock space content than $\bar{q}q$ is called a cryptoexotic or hidden exotic. We can also define flavour exotics to be those mesons with isospin equal or higher than $3/2$ or strangeness equal or higher than 2, since their minimal $\bar{q}q$ assignment is not allowed.

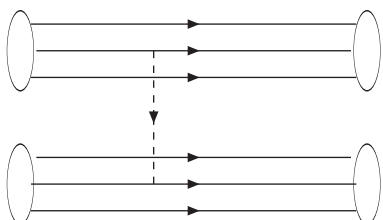
If it's not forbidden, it's mandatory

This old saying of quantum mechanics has a two-fold meaning in exotic spectroscopy. On one hand, the theory of the strong interactions does not forbid the existence of exotic mesons. They will therefore be found. Still they are obviously not the dominant form of strongly interacting matter, rather an oddity. This can be explained by the fact that they are subleading in a large N_c expansion, and by the mass gap that extra particles cost.

On the other hand this makes cryptoexotics a difficult task. All mesons with ordinary quantum numbers will have an ordinary $\bar{q}q$ leading Fock space assignment to some extent. In this respect, one should target searches to mesons with explicitly exotic quantum numbers for a clear discovery.

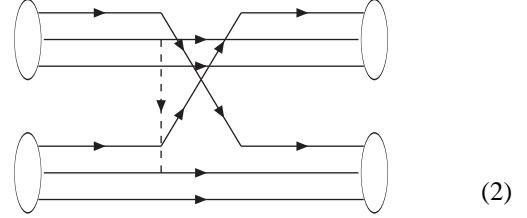
Exotic flavor channels are repulsive

The benchmark hadronic interactions like $\pi\pi$ scattering in an $I = 2$ wave, or KN scattering in $S = 1$, that had they shown resonant behaviour would have signaled exotic hadrons, are empirically repulsive. There is a quark model explanation within the Resonating Group Method [2] which I briefly sketch. First consider a hadron bound by an attractive color exchange modeled with a potential. The single exchange



(1)

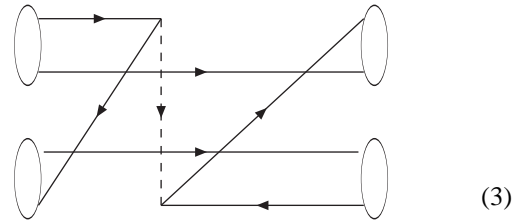
vanishes because of the color factor (two color singlets cannot exchange a color octet). With a Pauli exchange



(2)

the diagram gives a net repulsive contribution. This can happen only if the wavefunctions of both hadrons overlap (to allow the Pauli exchange) and gives rise to the core nucleon-nucleon repulsion that guarantees nuclear stability against collapse.

In the case of mesons, the constituent quark model cannot reproduce the low energy theorems that guarantee an attractive force to compensate this repulsion since the constituent quark mass explicitly breaks chiral symmetry. A simple field theoretical extension employing the Bethe-Salpeter equations [3] or the instantaneous Random Phase Approximation [4] allows for an annihilation diagram



(3)

that provides the necessary attractive force. This diagram vanishes unless the flavors of a quark and the antiquark in the other meson are equal. Therefore, in exotic flavor scattering where this flavor equality is not possible the repulsive interaction is not cancelled and exotic flavor channels remain usually repulsive, although with excited quantum numbers this can change. In the RPA some attractive diagrams in addition to this due to the back-propagating wave function are always present and help guarantee the Adler zero, but the interaction will remain repulsive although weak.

The argument is not valid at very low energies (where pion exchange is the dominant interaction, the deuteron binds after all) nor higher energies where the potential model has little to say.

A GLANCE AT THE SPECTRUM

The number of meson resonances is growing rapidly. There are now enough established (or firm candidates) to fill up to fourteen $SU(3)$ nonets (and meson spectroscopy is starting to resemble plant botanics). Some of the assignments below are controversial, but bear them for a moment as a starting point for the discussion. Older than me are the pseudoscalar $0^{-+} : [\pi K \eta \eta']$ and vector $1^{--} : [\rho K^* \omega \phi]$ nonets that correspond to the $L = 0, S = 0, 1$

quark model nonets (with a small D -wave mixing in the vector nonet). Of course, the charge conjugation assignments given do not apply to the open flavor mesons, and one should keep in mind possible mixing between states with equal J^P .

The quark model's $L = 1, S = 0$ nonet is also filled by 1^{+-} : $[b_1(1235), K_{1B}, h_1(1170, 1380)]$. Late developments [7, 8] indicate that we have now two scalar multiplets, one from the $q\bar{q}$ triplet $L = 1, S = 1$ 0^{++} : $[a_0(1450) K_0^*(1400) f_0(1370, 1710)]$ (with all the f_0 mixing, I am just counting states) and what looks like an S -wave dimeson molecule nonet 0^{++} : $[a_0(980) \kappa(900) f_0(600, 980)]$. The pseudovector (flavor) nonet of the (spin) triplet is also filled with 1^{++} : $[a_1(1260) K_{1A} f_1(1285, 1420)]$ and there are now two complete tensor nonets, for example the assignments 2^{++} : $[a_2(1320) K_2^*(1430) f_2(1430, 1525)]$ and 2^{++} : $[a_2(1700) K_2^*(1980) f_2(\text{various})]$. (or exchange one of the f_2 by the $f_2(1270)$). They lie too close to each other for radial excitations, so again we have a likely manifestation of meson molecules or four quark states with conventional $q\bar{q}$ mesons. Radial excitations do appear in the spectrum, and already in complete nonets. We can fill two more pseudoscalar nonets 0^{-+} : $[\pi(1300) K(1460) \eta(1295, 1440_H)]$ and 0^{-+} : $[\pi(1800) K(1830) \eta(1760, 2225?)]$ and almost two more vector nonets 1^{--} : $[\rho(1450) K^*(1410) \omega(1420)\phi(1680)]$ and 1^{--} : $[\rho(1700) K^*(1680) \omega(1650) \phi(\text{missing})]$. The higher one corresponds mostly to a D -wave, the lower to the radial excitation [6]. The lack of a ϕ meson at this scale is quite a puzzle and a challenge to DAΦNE. A comment from the audience informs us that in the B factories the next ϕ seems to appear well above 2 GeV . Even in the likely case of ideal mixing that would imply quite a high mass: we expect a value around 1.9 GeV . There are a number of other ρ resonances reported, $\rho(1900), \rho(2150)$... that having open flavor, should be accompanied by corresponding ω and ϕ mesons independently of their Fock space assignments. So there are plenty of opportunities for DAΦNE to clarify the situation if the beam energy is increased to 2 GeV . To complete the discussion let me comment on the higher angular momentum multiplets. The D -wave $L = 2, S = 0$ also seems to be complete with 2^{-+} : $[\pi_2(1670) K_2(1770) \eta_2(1645, 1870)]$. The corresponding $S = 1$ (mixing to G -wave possible) can be also assigned to 3^{--} : $[\rho_3(1690) K_3^*(1780) \omega_3(1670) \phi_3(1850)]$. Then a quark model F -wave, 4^{++} : $[a_4(2040) K_4^*(2045) f_4(2050, 2300)]$ and unless one is very interested in Regge theory or how the strong interactions depend on angular momentum, candidates to fill higher multiplets can be ignored for now.

Some mismatches

The particle tables collect an assortment of extra resonances that I do not mention here [1]. A few are worth

remarking though. There is an extra f_2 at low energy (I left out the $f_2(1270)$ for a cryptoexotic candidate, by which I mean a linear combination of the low energy f_2), then the $\eta_L(1440)$, both containing to some extent a four-quark component. Then an extra f_0 where again I left the $f_0(1500)$ to represent the appropriate combination of the f_0 's that likely construct the glueball state. If the dubious $K_2(1580)$ is confirmed we might have a K_2 in excess with the $K_2(1770)$ and $K_2(1820)$. Then some resonances are obviously missing: a b_1 around 1600 MeV would complete a second 1^{+-} nonet, an a_0 around 1800 would be an interesting addition to fill a 0^{++} nonet, there being a reported $K^{0*}(1950)$ (this automatically would pull two of the f_0 's out of the glueball candidate list, and there are some reported in the 2 GeV region). Also a K_1 in the 1.8 GeV region would make some $J = 1$ mesons fall in place, and outstandingly for this conference's purpose, a ϕ in the 1.9 GeV range is definitely expected.

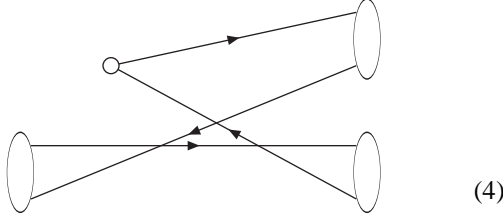
And some exotica

The firm candidates for explicitly exotic mesons are the 1^{-+} broad structures with mass and width $M = 1380(20) \text{ MeV}$, $\Gamma = 300(40) \text{ MeV}$ and $M = 1600(25) \text{ MeV}$, $\Gamma = 310(60) \text{ MeV}$. The first has a decay mode into $\eta\pi$, the second into $\eta'\pi$. A sensible account of the current status (and my favorite interpretation, see below) of these resonances is given in [10]. There might now be a third candidate around 1.9 GeV [9]. For very long these two states have been accused of being hybrid mesons, specially the second since it decays to the supposedly "glue rich" channel with an η' . These arguments do not resist closer examination and the trophy for a hybrid meson is still open. There is also a very interesting candidate, $X(1600)$ with reported isospin 2. If confirmed, this would be the first case of a meson with a *guaranteed* four-quark leading wavefunction [13].

Identification by decay patterns

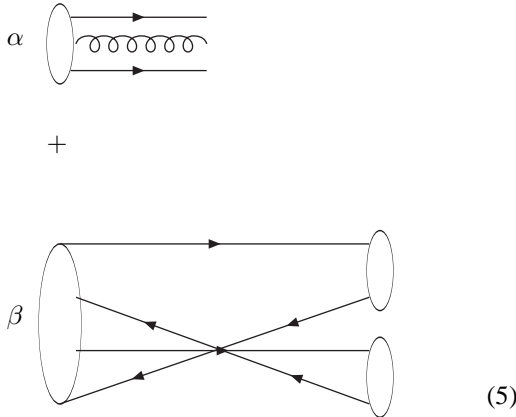
Beyond mass and width assignments, a detailed understanding of mesons requires predictions for their branching ratios into different possible open channels. The favorite model for these calculations is the 3P_0 model (T. Barnes has just completed a short historical account where references can be tracked [14]). In this mechanism, completing quantum-mechanical models of mesons such as the Constituent Quark Model or the Flux Tube Model at a fixed particle number, a $q\bar{q}$ pair is pulled out of the Fermi sea, and a rearrangement of color by a Pauli exchange leads to a two-meson decay. For example, for a conventional meson

one would have:



Within the 3P_0 model there are extensive decay calculations assisting experimental searches of hybrid mesons [15] in the flux tube model. (The decays of ordinary mesons have also been extensively studied). An outstanding prediction for hybrid mesons is their preference to decay to a pair of S - P mesons.

Let us also adopt the point of view of a Quantum Field Theory Hamiltonian. The first task is to perform a diagonalization in the Fock space to find the representation of the mesons in each channel, say for exotic meson $X = \alpha|q\bar{q}g\rangle + \beta|q\bar{q}q\bar{q}\rangle + \dots$. Then, once the Hamiltonian has been exactly diagonalized, the leading decay to two mesons proceeds by the wavefunction overlap of the four-quark component of the state with the state of two mesons streaming freely to the detector. That is, all two meson decays proceed via “Fall-Apart” decays of the four quark component. For a hybrid this mechanism can be depicted as



where any possible rescattering between the fermion lines in the second diagram should have already been taken into account in the construction of the various meson-fermion vertices, and the annihilation or absorption of the gluon in the first diagram should likewise already have been taken into account in the diagonalization of the Hamiltonian to construct the total wavefunction of the state. This diagram shows that *all* exotica decay to lowest order via its minimal multiquark component in a field-theoretical description (where “lowest order” refers to the wavefunctions of the final state mesons, that taken as conventional mesons, start with $q\bar{q}$, that is, lowest order in the constituent mass gap). Therefore, the hybrid wavefunction component of a meson hides behind the four (six) quark component as hadronic decays are concerned. Since the gluons do not

carry electric charge, similar considerations apply to radiative decays. This shows that until we have an excellent grasp of the physics of four and more quark states, we will not be able to fully trust predictions on the possible decays of exotica.

The result is unlike a lottery, where purchasing a ticket (detecting a J^{PC} -exotic meson) gives you a winning chance (an explicit gluonic excitation in the spectrum). Here until you have all the tickets in your hand you don’t collect your prize, since unravelling the wavefunctions in (5) is an arduous theoretical task, and we require knowledge of all excitations in the reasonable energy range for a given channel.

EXPLICIT GLUE

Glueballs

Glueballs are an interesting theoretical construction. Even without quarks, since chromodynamics is a non-abelian theory with non-linear gluon self-couplings, there would still be mesons. The spectrum has been calculated in the lattice on a number of occasions. The result of a well-known calculation is reproduced (courtesy of the authors of [16]) in figure 2.

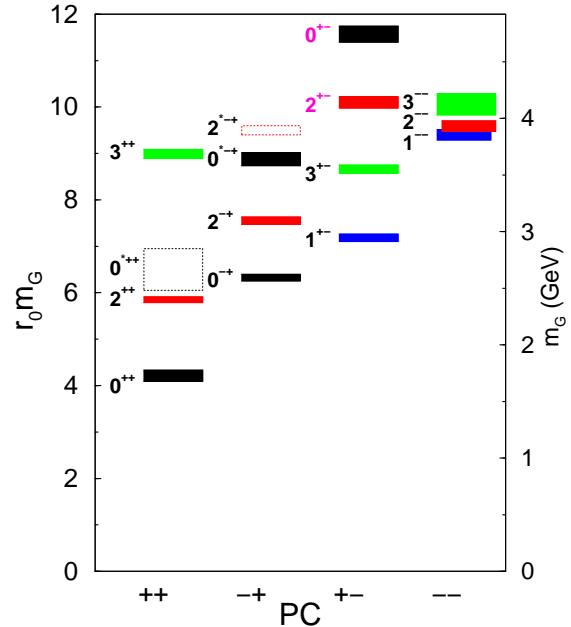


Figure 2: The lattice glueball spectrum (C. Morningstar and M. Peardon).

One sometimes wonders how inputting random numbers, valuable organized numbers are output, but this is so: the salient features of this spectrum are very well captured in model terms [18]. If one attempts to couple two massive constituent vector bosons in an S-wave to form a bound state, the possible quantum numbers would be $J^{PC} = (0, 1, 2)^{++}$. By observing figure 2 we see that the

1^{++} state is absent from the low-lying spectrum. Therefore a massive constituent gluon model fails. But a model with transverse gluons, such as based in the Coulomb gauge, automatically succeeds thanks to Yang's two-photon theorem. In these models, a gluon BCS mass-gap equation is solved that generates a gluon mass dynamically. Then the gluons can maintain their transverse nature since there is no explicit mass term and, being bosons, cannot couple to spin 1. Solution of the Tamm-Dancoff equation for the two-body problem provides a spectrum similar to the lattice results at low energy.

Another obvious feature in figure 2 is that odd-parity glueballs are heavier. This in two-gluon models follows from the necessity of a p-wave. The wavefunction $\langle s_1 m_1 s_2 m_2 | S m_s \rangle Y_L^{m_L}$ predicts the P -wave glueballs to have $J^{PC} = (0, 2, 3)^{-+}$. Finally, the negative charge conjugation states are even heavier, also natural in a model where a third gluon would be necessary (and again the mass-gap lifts this state).

The gluon mass gap can be predicted from this lattice data to be about 800-900 MeV . The lightest scalar glueball thus appears at 1600 MeV (or above) and the tensor glueball separated by a hyperfine splitting, slightly above 2 GeV . This mass gap is tied to the string tension calculated in the same lattice (the same happens in model calculations).

Finally the obvious remark that gluons carry no flavor quantum numbers, and therefore glueballs appear only as singlets in the spectrum, stirred through the f_0, f_2 families. A study to disentangle the glueball components [17] (with the approximation of ignoring four quark states) has found the scalar glueball to be shared between the $f_0(1370)$ and $f_0(1500)$ with some component in the $f_0(1710)$. This is based on decay predictions from flavor $SU(3)$ symmetry for $u\bar{u}, d\bar{d}$ and $s\bar{s}$ pairs and gives a qualitative picture of how difficult cryptoexotica may be: the only manifestation of this glueball state seems to be a supernumerary scalar meson.

Glueballs fall on Regge trajectories

Short of direct detection, a second window to glueballs and the gluon mass gap is provided by high energy physics. The interaction between static color sources at long distance follows a linear behavior, according to lattice QCD studies. This provides the theoretical basis for the linear potential and for the observation that mesons fall on straight lines in a plot of J versus M^2 (see figure 3).

Similar plots can be produced for baryons lending support to a diquark wavefunction clustering, but that is a theme for a different conference.

In Coulomb gauge QCD the potential interaction acts between color charge densities, and therefore the color charges associated to the gluons (after dynamical chiral symmetry breaking, also static charges) interact with a similar potential. A difference is the color factor for the potential exchange, 3 for gluon-gluon as opposed to $4/3$ for $\bar{q}q$.

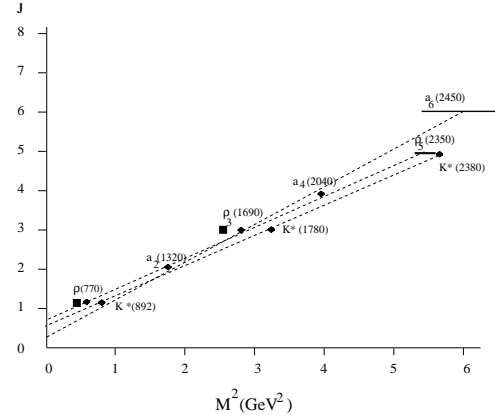


Figure 3: Some meson Regge trajectories.

This changes the slope of the Regge trajectories and brings them close to parallel to the famous pomeron Regge trajectory

$$J = 1.08 + 0.25t \quad (6)$$

equating $t = M^2$ we see that glueball exchange probably plays a role in total cross sections at high s , low t .

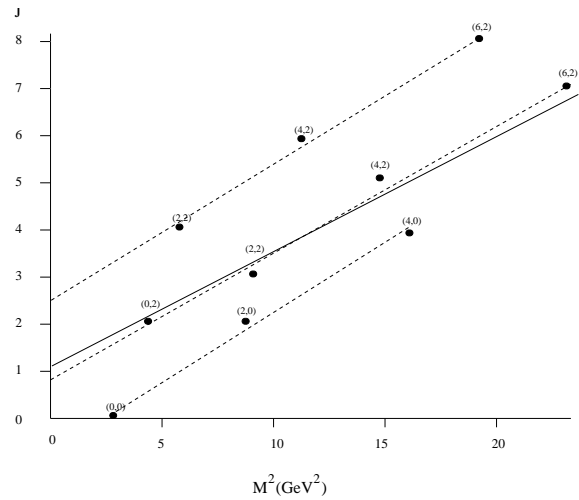


Figure 4: BCS/Tamm-Dancoff glueball spectrum with timelike Cornell potential between color charge densities. The wavefunctions are constructed in the Russell-Saunders scheme and configuration mixing is not included. The solid line is the pomeron Regge trajectory. States following to the left of it are unphysical and their low mass is probably due to excessive spin-orbit coupling.

Our glueball calculations [18, 19], based on QCD time-like vector exchange, suffer from an excessive spin-orbit coupling. This is analogous to the same phenomenon in the quarkonium spectrum, that leads spectroscopists to hypothesize scalar confinement. Therefore, to extract relatively model-independent information from our model glueball spectrum, we should look at states with a vanishing expectation value of $L \cdot S$. This is achieved if either $L = 0$ or $S = 0$. For $S=0$ there is a Regge trajectory formed by

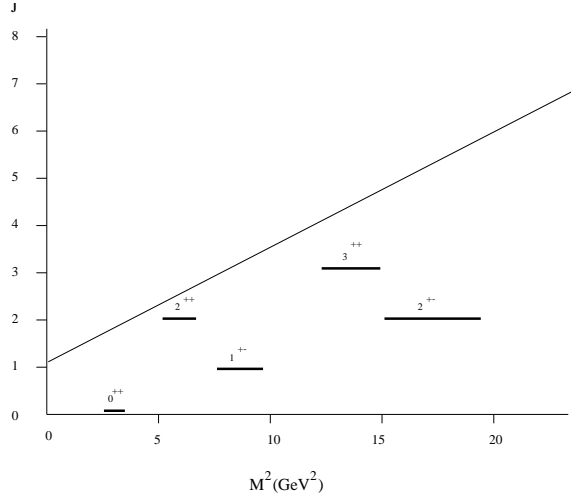


Figure 5: Lattice glueball states also seem to fall on Regge trajectories. The 4^{++} state, with larger error bars, recently calculated, is compatible with the pomeron trajectory.

the glueballs $L = 0, 2, 4, \dots$, $J^{PC} = (0, 2, 4\dots)^{++}$ that passes by the lightest scalar glueball, parallel and below the pomeron trajectory. From this, the slope of all glueball Regge trajectories can be extracted. There is still the $L = 0$ case. With $S = 0$ we recover the scalar glueball. But with $S = 2$, the lowest-lying tensor glueball 2^{++} does not suffer from spin-orbit corrections and therefore we can confidently calculate its mass. We find it just above 2 GeV , and almost within lattice error bands, it falls right on the pomeron Regge trajectory. Other glueball states with quantum numbers J^{++} calculated in the lattice seem to also fall on the pomeron trajectory, here the error bands being considerably larger.

In a more elaborate model we would expect glueballs with $L = 2, L = 4, \dots$ and spins aligned to also fall on or near the pomeron Regge trajectory. Currently this is not the case since our large spin-orbit coupling pushes these states left of the pomeron trajectory (in contradiction with total energy cross section growths). Therefore further work is required to improve the current models. Similar results are reported by other authors [20] with Regge trajectories that start bending and behaving non-linearly.

As a conclusion, we expect fits to high energy cross-sections to provide a complementary approach to low energy spectroscopy in the understanding of gluonic excitations.

It is also interesting that the odderon, Regge pole exchange with negative C -parity, would produce differences between the $p\bar{p}$ and pp cross sections that are not experimentally observed. Within our constituent approach this is again easy to understand, as negative parity glueballs require a third gluon and thus lie to the right of the pomeron trajectory and are less relevant for high s scattering.

Hybrid Mesons: quantum numbers

Hybrid mesons are also defined only with the help of a model. From the few-body point of view [21, 22] in that the quark-antiquark pair are accompanied by an explicit constituent gluon (or in our models, a quasiparticle-gluon after dynamical chiral symmetry breaking), it is a relatively simple task to predict the quantum numbers of lowest lying hybrid states. Consider the three-body system in its center of momentum (CM) frame. The remaining six momentum space coordinates can be chosen as

$$q_+ = (q + \bar{q})/2 \quad q_- = q - \bar{q} \quad (7)$$

(the gluon's momentum is immediately determined in the CM frame). There are three particle spins, the quark and antiquark s_q and $s_{\bar{q}}$ and the gluon spin s_g . All angular momenta can be then added

$$s_q + s_{\bar{q}} + s_g + L_+ + L_- = J \quad (8)$$

with the usual angular momentum rules. Of the several possible recouplings we choose to combine s_q and $s_{\bar{q}}$ to spin S since then one can form (for equal $q\bar{q}$ flavor) eigenstates of charge conjugation with eigenvalue

$$C = (-1)^{1+S+L_-} \quad (9)$$

Since the gluon is a vector state it brings an additional (-1) to the parity computation yielding

$$P = (-1)^{L_++L_-} \quad (10)$$

The lowest lying states are expected to be those with $L_+ = L_- = 0$, and the possible combinations are therefore $J^{PC} = 1^{+-}, (0, 1, 2)^{++}$. These have conventional quantum numbers and mix with ordinary $q\bar{q}$ mesons. Allowing for a P wave we have either $L_- = 1$, $J^{PC} = 0^{-+}, (1, 2)^{-+}, (0, 1, 2, 3)^{--}$ or $L_+ = 1$, $J^{PC} = (0, 1, 2, 3)^{-+}, (1, 2)^{--}$ with various multiplicities due to the intermediate spin states.

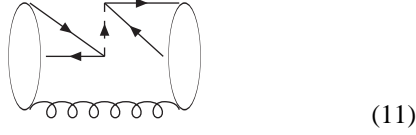
In our model calculations the L_+ excitation is less expensive energetically (L_- can be taken as the variable conjugate to the quark-antiquark position, that see a net repulsion in a color octet) Therefore the lightest exotic hybrid mesons have quantum numbers $1^{-+}, 3^{-+}$ and 0^{--} in this approach.

Hybrid mesons: masses

Our model calculations with a variational approach and a modest wavefunction basis (hence, upper bound to the minimum eigenvalues) concludes there are no hybrid states, below 2 GeV . This is somewhat high compared to lattice expectations that estimate the first hybrid to lie around 1.9 GeV . In this there is not unanimous agreement, as recent calculations point to 1.7 GeV [23] and 2.1 GeV [24] for the lowest lying 1^{-+} exotic hybrid.

As flavor is concerned, hybrids come in flavor nonets as their regular $q\bar{q}$ counterparts. Isospin $I = 1$ hybrid mesons

are expected to be lighter than $I = 0$ as the following annihilation diagram



is only possible for isospin zero, and adds about 200 MeV to the mass of these states.

An alternative description is provided by the flux tube model [11], inspired in lattice QCD in the limit of strong coupling. Not surprisingly, the model (usually combined with the Born-Oppenheimer approximation for heavy quarks) is in good agreement with lattice data for $bg\bar{b}$ states [25]. For light hybrid states, the model predicts isospin 1 multiplets with quantum numbers $(0, 1, 2)^{+-}$, $(0, 1, 2)^{-+}$, 1^{++} , 1^{--} at about 1.9 GeV . The mass difference with our approach can be explained by the fact that this string simulating a flux tube provides for a color singlet potential (therefore attractive) between the quark and antiquark also in the excited (hybrid) configuration, whereas in an approach with an explicit QCD gluon the quark and antiquark are in a color octet configuration, repulsive. If the original flux-tube model is corrected employing the lattice excited adiabatic potential instead of the attractive Coulomb tail from Isgur and Paton, the mass predictions rise again to above 2 GeV [26].

In any case, both approaches concur to predict exotic hybrids to be well above the two experimental candidates (in disagreement with old bag model calculations [27]).

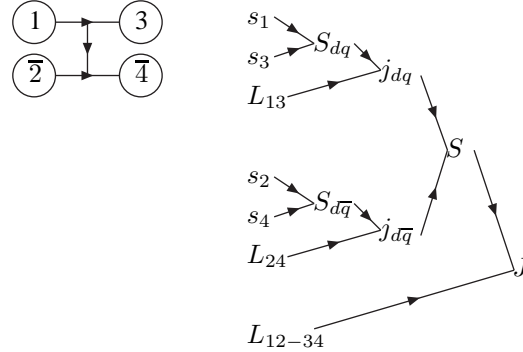
Given the large number of channels and possible angular momentum combinations, the spin splittings due to fine and hyperfine interactions in hybrid mesons, that lift the degeneracies between the various J^{PC} , are quite intricate. Within our few-body approach, the relativistic structure of the Hamiltonian provides for some splittings, but the γ_0 time-like vector potential is known to be deficient in the ordinary meson sector, leaving this as an open issue. These splittings have been calculated in the context of the Flux Tube Model [26] and lift the degeneracy between the vector 1^{--} and exotic 1^{-+} hybrid mesons.

All theoretical approaches seem to concur that vector hybrids in the charmonium system should appear at about 4.4 GeV . In our calculations, up to four hybrid states appear around the last known $\psi(4415)$ resonance (and suggest above it a continuum that would require careful work to discern the various states).

MULTIQUARK STATES

Four quark states

Constructing the angular momentum wavefunctions for $qq\bar{q}\bar{q}$ is long to describe, so let me do it with a picture:



$$C = (-1)^{S+L_{12-34}}$$

$$P = (-1)^{L_{13}+L_{24}+L_{12-34}}$$

With all $L = 0$, the wavefunctions that can be constructed have conventional quantum numbers $(0, 2)^{++}$, 1^{+-} , 1^+ . If we allow a P -wave, then also possible are 1^{--} , $(0, 1, 2, 3)^-$, $(0, 1, 2)^{-+}$. These assignments can proceed in various ways through the angular momentum tree, and therefore there are several possible constructions of each state. This leads to a rich spectrum first calculated in the bag model [28] that leads to the so called *state inflation* not experimentally observed, although the light scalars at least seem to fill the S -wave nonet. They are very broad as expected for wavefunctions with an OZI superallowed “fall apart” decay.

Notice the (unfortunate?) coincidence that the lowest exotic seems to be the 1^{-+} and that four quark states are predicted to be lighter than hybrids. With the angular momentum construction above there is a unique way of constructing this state. But to build an isospin 1 state one can of course resort to $(u\bar{u} + d\bar{d})u\bar{d}$ or $s\bar{s}u\bar{d}$, and therefore two light, broad four quark structures are expected in agreement with observation. In other channels they may just be assigned to background as more prominent $q\bar{q}$ resonances appear, but in this exotic channel they have to be the first structures appearing. In this sense, the other exotic quantum numbers that hybrid mesons span are more promising.

On occasion of another DAΦNE workshop, Badalyan presented his results for four quark states [35]. Since these calculations have to my knowledge not been superseded by subsequent studies (given the lack of experimental motivation), I abstract in table 1 the result for the center of gravity of the spin multiplets for the ground state. In both Jaffe’s and Badalyan’s work the scalar mesons are lightest, and the large (unreliable) spin splittings make further progress difficult. The lightest exotic 1^{-+} was predicted at 1.7 GeV .

Another problem with these calculations is their lack of agreement with the low energy pion theorems: in channels where broad structures decay to light Goldstone bosons, one would expect chiral symmetry to play a major role. Only recently it was understood how to incorporate chiral symmetry into calculations beyond the spectrum through the RPA/Bethe-Salpeter approach [5] and we may expect

Table 1: In this table we give the center of mass (prior to spin splittings) of the four quark ground state in terms of its flavor content. Ideal mixing is expected to hold in four-quark systems.

M(flavor)	Badalyan(1987,1991)	Jaffe(1977)
4 light q	1565	1540
2 light 2 s	1950	1800
4 s	2260	2150

progress in this direction.

In the vector 1^{--} channel the four quark *state inflation* leads to a prediction [35, 36] of a large number of states, at 1500, 1660, 1830, 1860, 1940, 2000, 2070 MeV and this is not acceptable with our current understanding of the data. Here is interesting work for theorists. Initially we may assume they are broad and overlapping.

An exception to the rule that four-quark states are broad can be found in the $f_0(980)$ because it is just below its natural two kaon decay. This may happen again to some extent, so a number of interesting thresholds (like the two ω , two ϕ or two nucleon) are worth detailed scrutiny.

Among theorists, there has been some skepticism about four-quark states (with the exception of the light scalars), that can (other than by lack of direct evidence) partly be tracked to the work of Weinstein and Isgur [29] who, conducting a variational calculation containing $qq\bar{q}\bar{q}$ in the basis, found separate hadron states to be lighter than compact multiquarks. This has the advantage of providing some support for the nuclear physics picture where nuclei are clusters of nucleons, not of quarks.

The Pentaquark

This expectations are at odds with the recent detection [30] of a pentaquark. Although a baryon, this state opens new perspectives in meson spectroscopy. This state, at 1540 MeV , has been observed to decay to pK_0 and nK^+ . The threshold for this channel is 1435 MeV and therefore there is sufficient phase space for the decay. The width of this $\Theta^+(1540)$ state is intriguingly narrow, less than 10 MeV. More interesting is the fact that its leading wavefunction assignment in Fock space has to be $|uudd\bar{s}\rangle$ and is therefore flavor exotic. If further confirmed beyond the present experimental data, this state supposes a true revolution in spectroscopy.

We could ask ourselves if this state is a molecule in the sense of the $f_0(980)$ or deuterium. But the KN interaction is repulsive in an S -wave, and only very mildly attractive in a P -wave (recall our general discussion about exotic channels being repulsive). Therefore the system does not resonate. It has been suggested [31] that a pion would stabilize the system to form a three body state $K\pi N$. We have performed standard calculations within the Chiral La-

grangian supplemented with unitary (Lippman-Schwinger) techniques [32] and found there is indeed attraction in the $J^P = \frac{1}{2}^+$ channel preferred by theorists, but way insufficient to bind the system. This is consistent with the low energy database accumulated through the years: only at higher energies around 1800 MeV there have been persisting hints [33] of resonances that could fit into a molecular-type approach, collectively called Z^* .

Therefore if this state is confirmed, it will have to be assigned to a compact pentaquark structure bound by QCD forces. And open many questions as to what other multi-quark states are there, and where.

Six quark states

At least one six quark state obviously exists (deuterium). It can be argued that it is totally a molecular state given its large radius and small binding energy. The question here is whether a six quark meson can be found. The obvious place to look is just under (around?) the two nucleon threshold. Along the years intermitent data have supported the existence of baryonium, with no conclusive evidence to date.

Lately there are promising candidates in the reaction $J/\Psi \rightarrow \gamma p\bar{p}$ at BES [37] and in multipion production processes [38]. The BES results are compatible with a 0^{--} resonance, that would suggest parabaryonium has been found (the analogous of the pion with $L = 0$, $S = 0$, instead of a quark, a proton, and instead of an antiquark, an antiproton). This state has the proton and antiproton spins antialigned, and it should be accompanied by an almost degenerate vector state, 1^{--} (orthobaryonium) that is a prime candidate for searches at DAΦNE with an enhanced energy beam. These resonances are expected to be narrow (by the necessity of annihilating that large number of valence quarks and the OZI rule), just below NN threshold and with suppressed $K\bar{K}$ decays (no strange valence content in either of the constituents).

An interesting question is whether this state appears in all possible channels $n\bar{n}$, $n\bar{p}$, $p\bar{n}$, $p\bar{p}$, or just in the latter. In this case we could still argue on a nucleon-antinucleon state loosely bound by QED forces alone, violating isospin symmetry (alternatively something totally different as one of the mentioned four-quark states or a hybrid state would be a possibility in this mass range).

In any case, since the quark model assignments for vector $q\bar{q}$ states predict the D -wave vector comfortably close to the $\rho(1700)$ and the next radial excitation is above 2 GeV , any vector resonance in the interval of energies 1.8 – 2.0 GeV is a prime cryptoexotic candidate.

CONCLUSIONS AND OUTLOOK

I hope to have conveyed to you some of the excitement in light exotic spectroscopy. In my view, below 1.6 GeV we have already a state saturation and the identification of the wave function components of four quark states is the most interesting problem. Above 1.6 GeV many conven-

tional, let alone exotic and cryptoexotic are missing. To what extent they can be separated from one another and the continuum they form in most hadronic processes is a question of intelligent filters, multiple particle decay analysis and hard labor.

The most intriguing excitations are those containing some sort of glue – glueballs and hybrid mesons, but they are hiding behind the purely quark (let it be two or four...) wavefunctions in each channel. The model is the scalar glueball, probably already in our pocket as a supernumerary f_0 (in fact, as a good quantum state, in both pockets at the same time). We expect the situation with the tensor glueball to be the same: just hard work ahead in the 2^{++} meson channel.

For hybrid mesons the situation would seem cleaner because of the possibility of exotic quantum numbers. But this is misleading since four quark states hide a hybrid as effectively as two quark states hide a glueball. The experimentally studied case, with 1^{-+} quantum numbers is the model. Other exotic waves should (and probably will, in experiments like COMPASS or GLUE-X) be explored.

To correctly identify these excitations they need to be separated from four-quark states, about whom very little is known. In turn, the best grasp on these states comes from flavor exotic waves. These are generally repulsive at low energies, but the possible detection of a pentaquark now should make us rethink about them. At higher energies more careful scans should be conducted.

What contribution can DAΦNE make? If the other important physics issues addressable by the upgraded machine allow the beam energy to be increased to 2 GeV , then with its high luminosity it could make the best map of the $1.7 - 2\text{ GeV}$ energy interval where some interesting states may appear. To be really competitive with other experiments though, 2.5 GeV would be much better. Then the vector isoscalar channel could be really mapped out to much higher energies, and the decay products would naturally span the $1.5 - 2\text{ GeV}$ region with different quantum numbers.

The interested reader can find more information in the recent overview of Curtis Meyer [9] where lots of tables and data are given that I do not reproduce here. Another source of information is the Exotica Web page <http://fafnir.phyast.pitt.edu/exotica/>.

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First I want to thank the present and former group at North Carolina State University for attracting my interest to the problems of exotic spectroscopy. I also would like to thank the organizers of this workshop for the invitation to give a perspective of the field. I tried to keep the presentation pedagogic to attract the wider audience, and apologize to a few experts attending the session who had to hear again known statements. I also would like to apologize to the authors of an immense number of papers that compose our knowledge basis of the field and whose names do not ap-

pear in the following minimal reference list. This work was supported by Spanish government grants FPA 2000-0956, BFM 2002-01003.

Since the first posting of this work two related papers have appeared. One by J. E. Ribeiro refreshing on the RGM methods [39], one by E. Swanson, whom I thank for some useful comments on the manuscript, proposing a four quark state assignment for the new charmonium state $X(3872)$ with a specific dynamical model [40].

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